Signal Detection

- ✓ the RF pulse generates transverse magnetisation M_{xy}
- ✓ In the rotating frame this magnetisation is stationary and orthogonal to B_1 direction

<u>In laboratory frame</u>

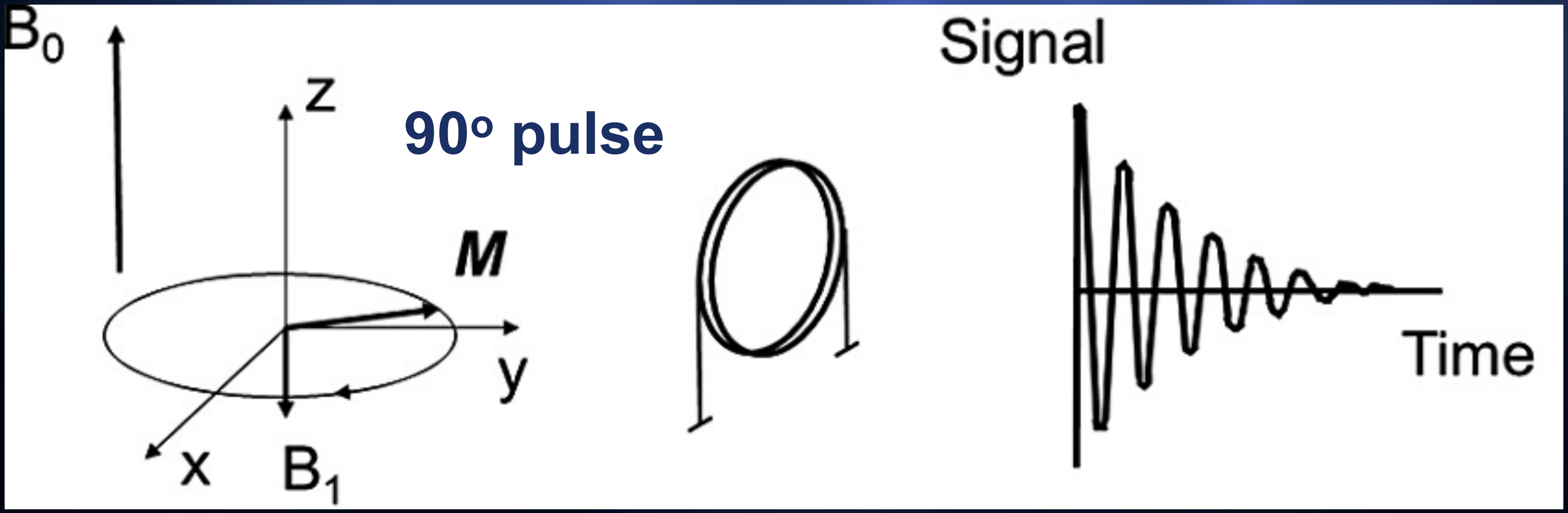
$$M_z = |\mathbf{M}| \cos(\gamma B_1 t_{RF})$$

$$M_y = |\mathbf{M}| \sin\alpha \cos\omega_0 t = |\mathbf{M}| \sin(\gamma B_1 t_{RF}) \cos\omega_0 t$$

$$M_x = |\mathbf{M}| \sin\alpha \sin\omega_0 t = |\mathbf{M}| \sin(\gamma B_1 t_{RF}) \sin\omega_0 t$$

Signal Detection

- ✓ M_{xy} is a time-varying magnetisation
- ✓ Faraday's law
  - changing magnetisation generates an electromotive force in a nearby electrical conductor
    - ❖ EMF or voltage
  - If conductor is connected to a circuit, an electric current flows and can be detected

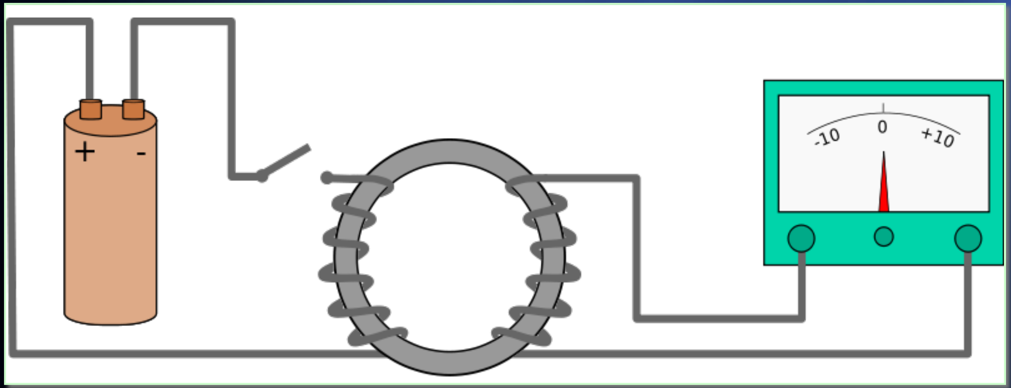


Basic Concepts
Faraday's law

$$\varepsilon = -N\frac{d\Phi_B}{dt}$$

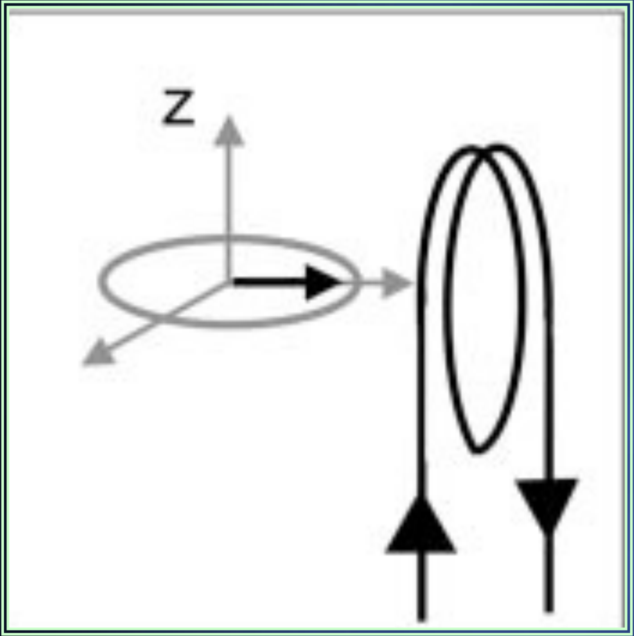
$\phi_B = B\,S\,cos\theta$

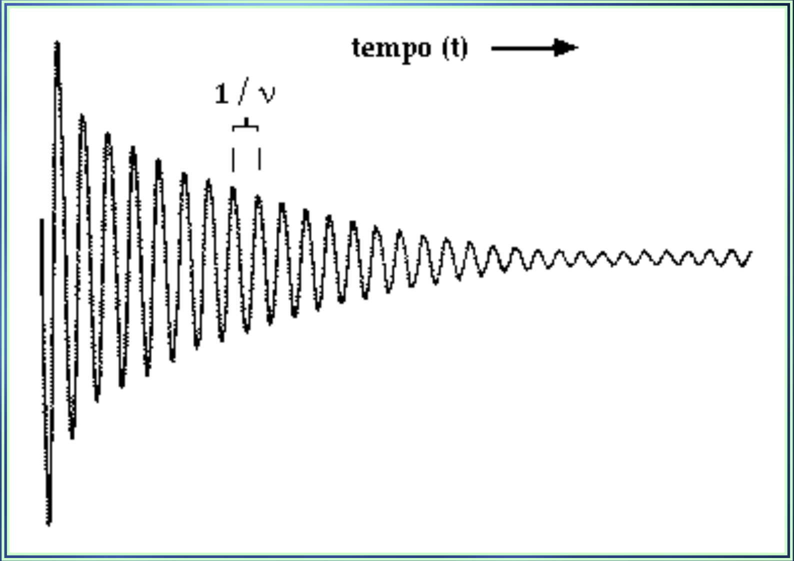
ε electromotive force
Φ_B magnetic flux
N number of identical turns



A Faraday's iron ring apparatus:
Change in the magnetic flux of the left coil induces a current in the right coil

FID
free induction decay signal



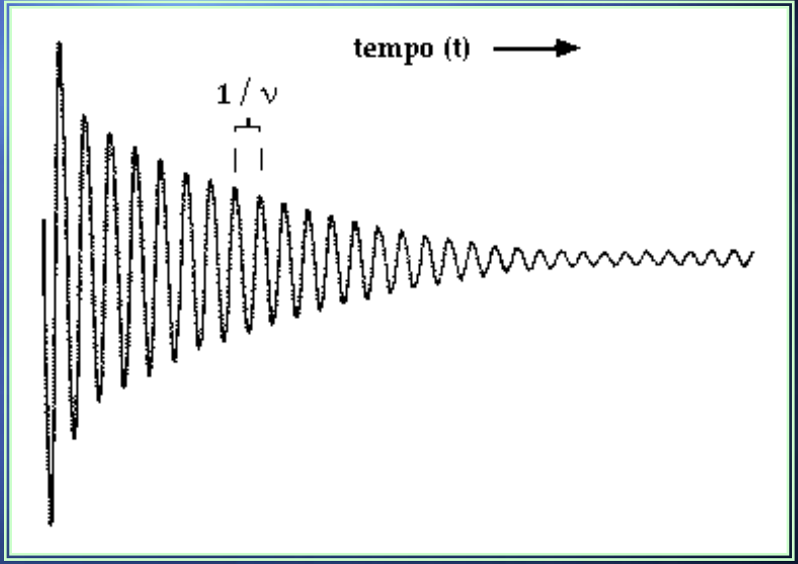


- ✓ Coil is both transmitter and receiver

- ✓ Exponentially damped sinusoid
  - Relaxation
- ✓ FID disappears within a few hundred milliseconds
  - The surroundings absorbs energy

Nuclear relaxation

- ✓ FID signal does not persist indefinitely
  - decays exponentially



2 descriptions

- ✓ macroscopic scale
- ✓ individual nuclei

Nuclear relaxation

After a 90° pulse

- ✓ longitudinal magnetisation M_z

$$M_z = |\mathbf{M}|\left(1 - e^{-\frac{t}{T_1}}\right)$$

- ✓ transverse magnetisation M_{xy}

$$M_{xy} = |\mathbf{M}| e^{-\frac{t}{T_2}}$$

https://www.imaios.com/en/e-mri/nmr/relaxation-times

T_1 relaxation

the first Bloch equation

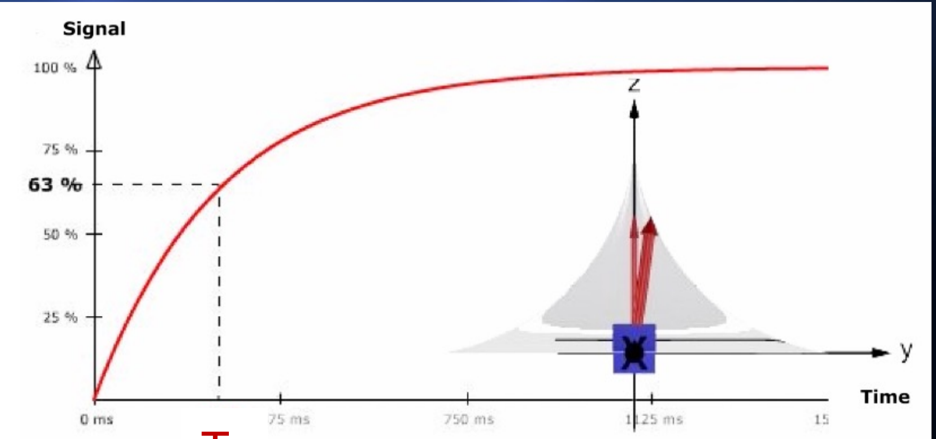
$$\frac{dM_z}{dt} = -\frac{(M_z - M_0)}{T_1}$$

- ✓ T_1 longitudinal relaxation time
  - or spin lattice relaxation time

$$M_z = |\mathbf{M}|\left(1 - e^{-\frac{t}{T_1}}\right)$$

Solution for a 90° pulse

https://www.imaios.com/en/e-mri/nmr/relaxation-times



T_1

T_2 relaxation

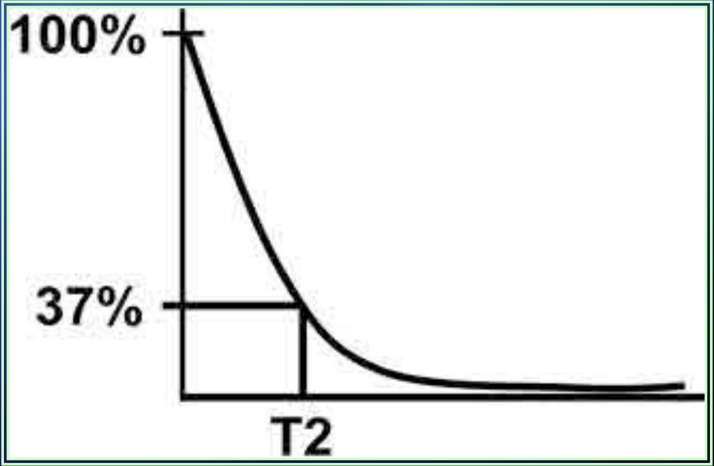
Second Bloch equation

$$\frac{d}{dt}M_{xy} = -\frac{M_x i + M_y j}{T_2^*}$$

- ✓ T_2 transverse relaxation time
  - or spin–spin relaxation time

$$M_{xy} = |\mathbf{M}| e^{-\frac{t}{T_2}}$$

Solution for a 90° pulse



T2 and T2 are different and will be discussed later*

T_1 and T_2 relaxation

- ✓ determined by the chemical environment
  - water content
- ✓ vary between different body tissues and between healthy and diseased tissue
  - main source of contrast in conventional MR images

T_1 and T_2 relaxation

[1]H NMR Relaxation Times of Brain Tissues Measured at 1.5 T		
Tissue	**T1 (ms) (mean ± SD)**	**T2 (ms) (mean ± SD)**
Grey matter	1078 ± 53	100 ± 12
White matter	684 ± 21	79 ± 12
Cerebrospinal fluid (CSF)	3959 ± 306	914 ± 422

T_1 depends on the B_0 strength

T_1 and T_2 relaxation

[1]H NMR Relaxation Times of Brain Tissues Measured at 1.5 T

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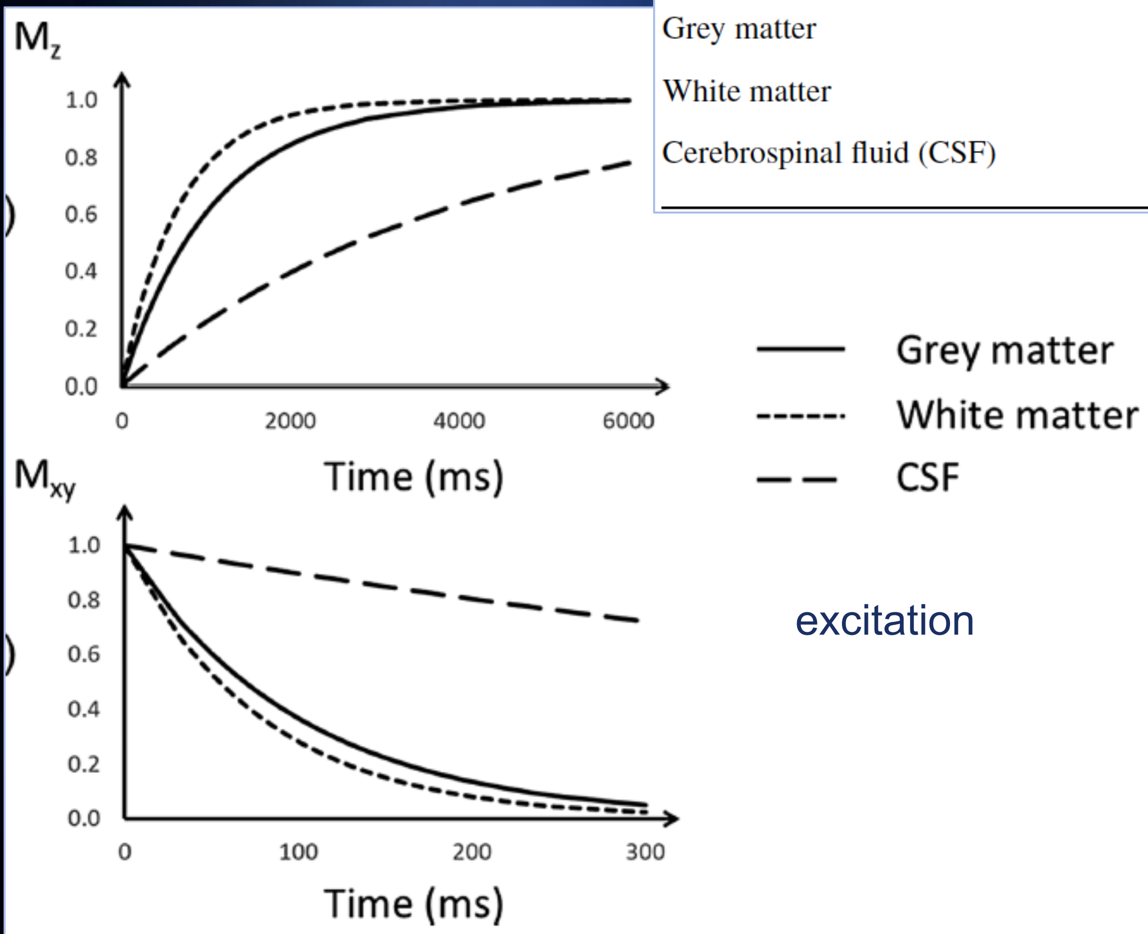
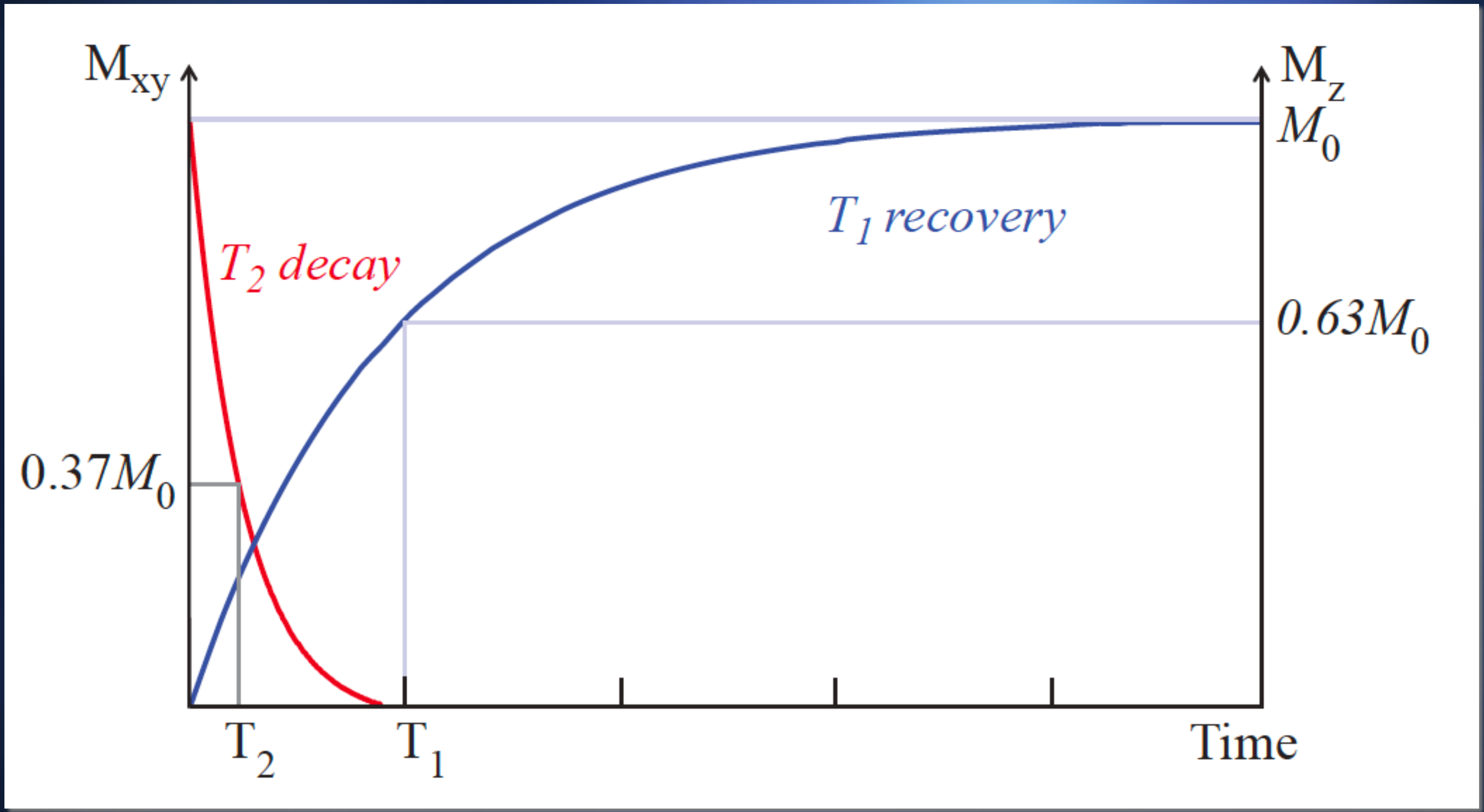


excitation

relaxation

https://www.imaios.com/en/e-mri/nmr/relaxation-times

Relaxation times



Tissue	T1 (ms) (mean ± SD)	T2 (ms) (mean ± SD)
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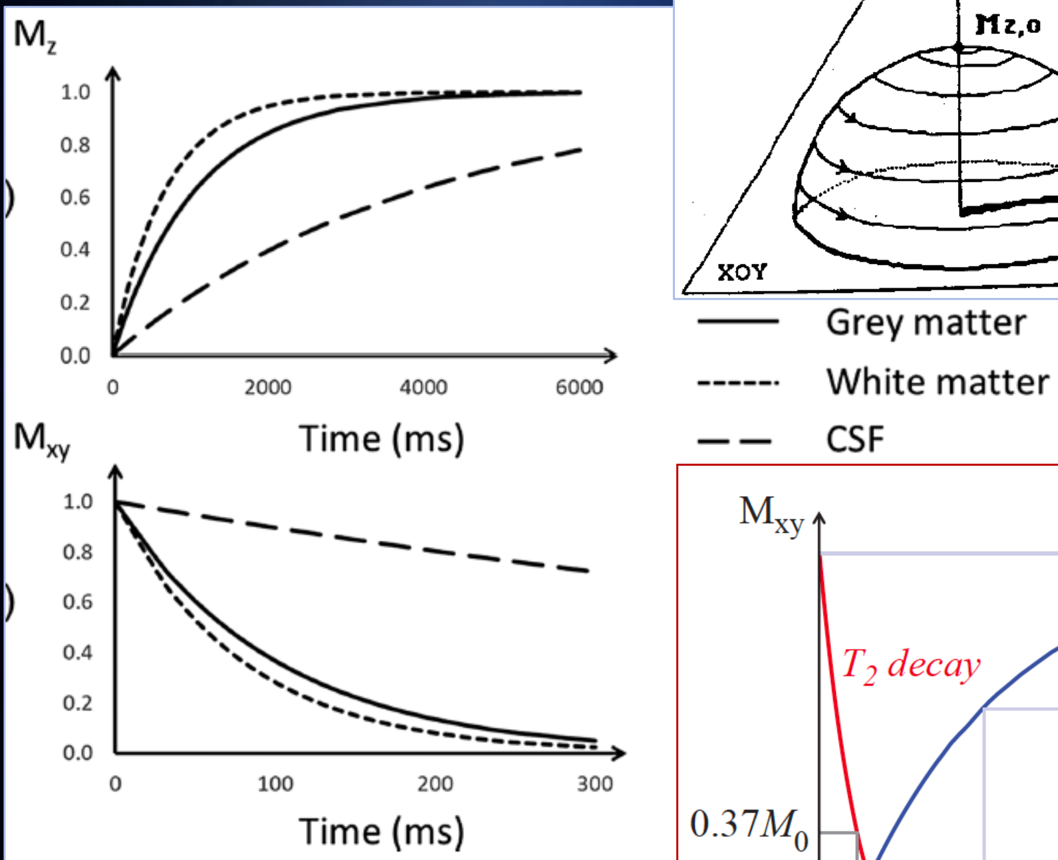
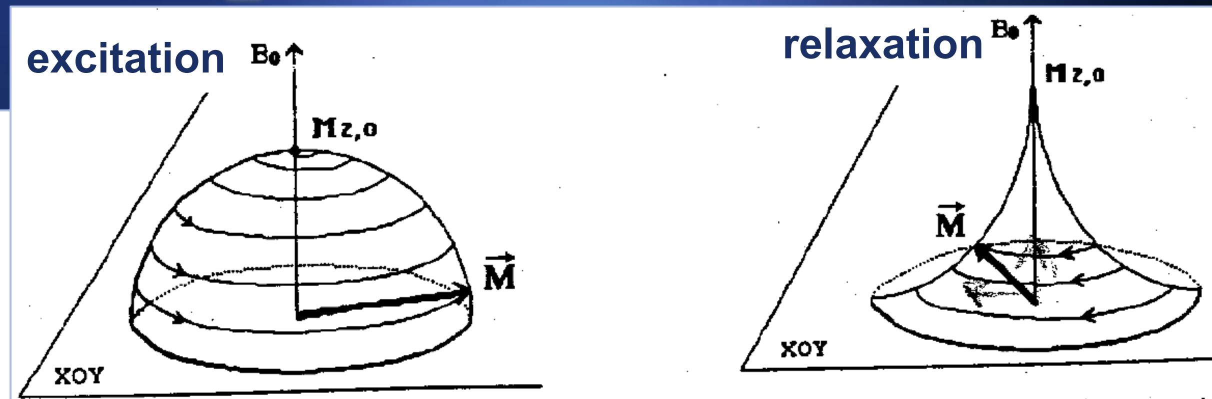
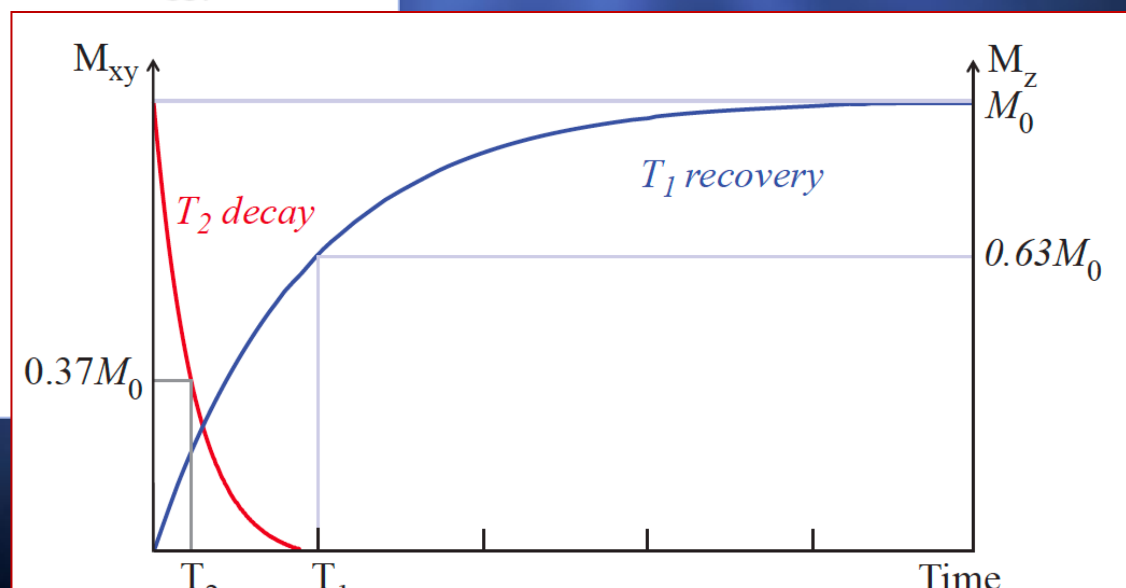
T_1 and T_2 relaxation







https://www.imaios.com/en/e-mri/nmr/relaxation-times

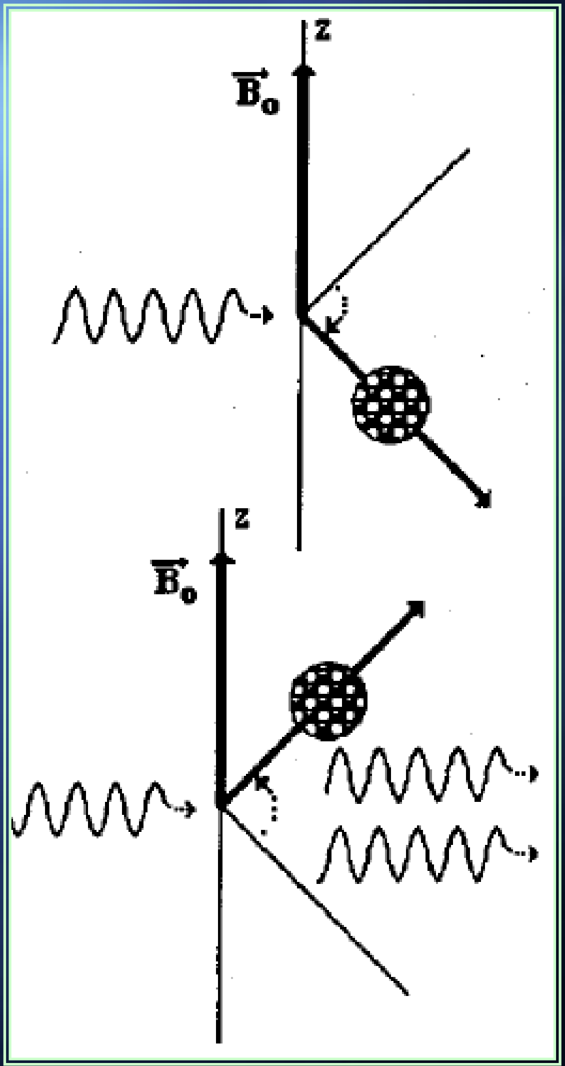
Relaxation and quantum mechanics

- ✓ nutation of the M results from absorption of energy from the RF field
  - exciting nuclei from the lower energy level to the higher one
- ✓ Relaxation occurs when an excited nucleus releases the ‘‘quantum’ of energy that it has absorbed
  - returning as a result to the lower energy level

T_1 relaxation

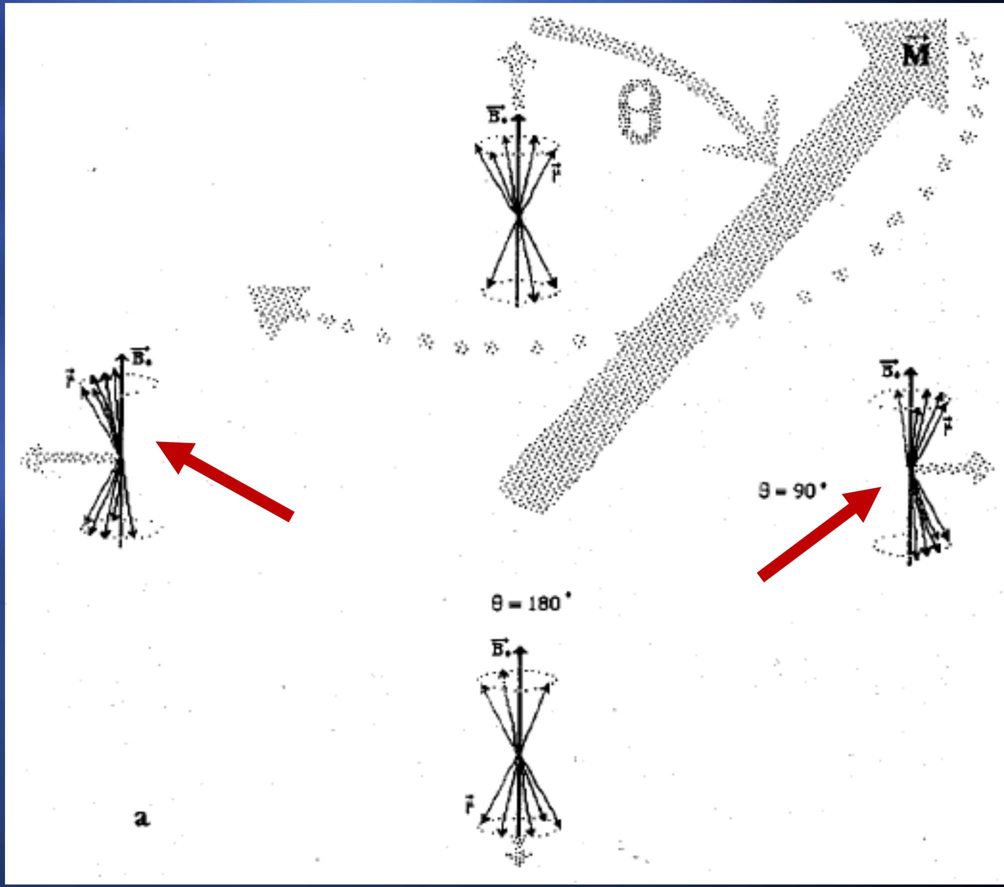
The transitions from spin-down to spin-up (lower energy state)

- ✓ are not spontaneous
- ✓ are stimulated by fluctuating magnetic fields produced by molecular motions
    - Chemical enviroment



Phase and NMR signal

- ✓ the RF pulse made the excited nuclei to precess in phase with each other
- ✓ so that M_{xy} is generated in the transverse plane



T_1 Quantum mechanics

- ✓ If the quantum of energy is lost from the spin system, there is an increase in the population of the higher energy level
- ✓ resulting in an increase in M_z
  - T_1 relaxation
- ✓ the emitted quantum of energy is absorbed by the surrounding environment
  - known as the lattice
    - spin-lattice relaxation

T_2 Quantum mechanics

- ✓ alternatively, the emitted quantum is absorbed by another nucleus in the lower energy level
  - so that 2 nuclei swap places and there is no net increase in M_z
- ✓ the newly excited nucleus will not be precessing in phase with the other nuclei excited by the RF pulse
- ✓ M_{xy} will be reduced
  - T_2 relaxation
    - ❖ or spin–spin relaxation

T_2 & T_2*

- ✓ the exponential decay of the FID is faster than T_2 alone would suggest
- ✓ The cause of the difference lies in microscopic inhomogeneities in B_0
- ✓ B_0 uniformity of MRI equipment is quite good
  - usually within 1 ppm (0.0001%) of 1.5 T over a 40 cm diameter spherical volume (DSV) at the centre of the bore

T_2 & $T2^*$

✓ The effective decay time is T_2^*

$$1/T_2^* = 1/T_2 + \gamma\Delta B$$

- In pure liquids:
  $\gamma\Delta B \gg 1/T_2$

Effects That Cause T2* and T2 Dephasing	
Causes of T2* Dephasing	Causes of T2 Dephasing
Spin-spin interactions	Spin-spin interactions
Magnetic field inhomogeneities	
Magnetic susceptibility	
Chemical shift effects	

✓ When the patient is introduced into the scanner the field is distorted on a microscopic scale because of the differing magnetic properties of different tissues and structures

- magnetic susceptibilities

http://www.imaios.com/en/e-Courses/e-MRI/MRI-signal-contrast/90-RF-pulse

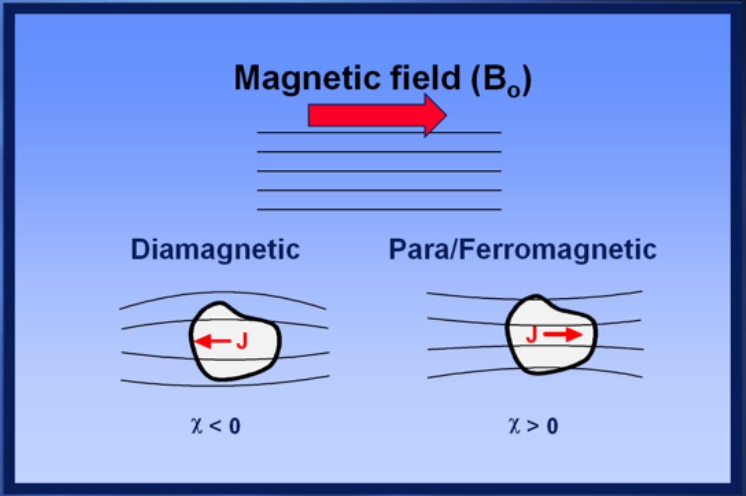
T_2 & $T2^*$

✓ The effective decay time is T_2^*

$$1/T_2^* = 1/T_2 + \gamma\Delta B$$

- In pure liquids:

  $\gamma\Delta B >> 1/T_2$



✓ When the patient is introduced into the scanner the field is distorted on a microscopic scale because of the differing magnetic properties of different tissues and structures

- magnetic susceptibilities

http://www.imaios.com/en/e-Courses/e-MRI/MRI-signal-contrast/90-RF-pulse

T_2 & $T2^*$

✓ **The effective decay time is T_2^***

$$1/T_2^* = 1/T_2 + \gamma \Delta B$$

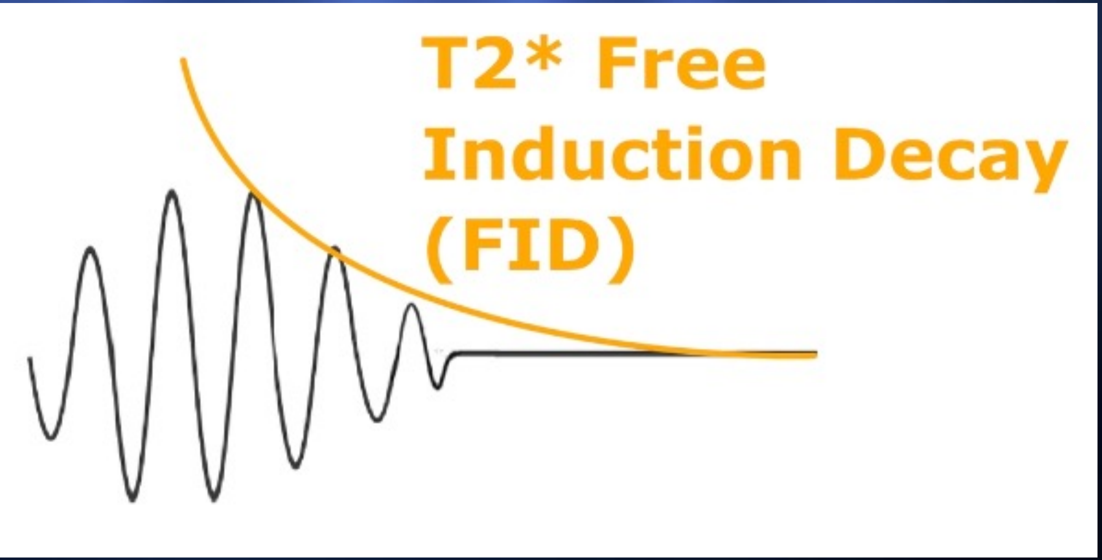
- In pure liquids:

  $\gamma \Delta H \gg 1/T_2$

Effects That Cause T2* and T2 Dephasing

Causes of T2* Dephasing	Causes of T2 Dephasing
Spin-spin interactions	Spin-spin interactions
Magnetic field inhomogeneities	
Magnetic susceptibility	
Chemical shift effects	

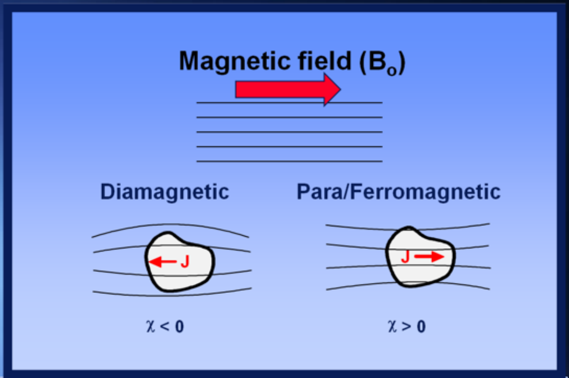
$$M_{xy} = |\mathbf{M}| e^{-\frac{t}{T_2 *}}$$

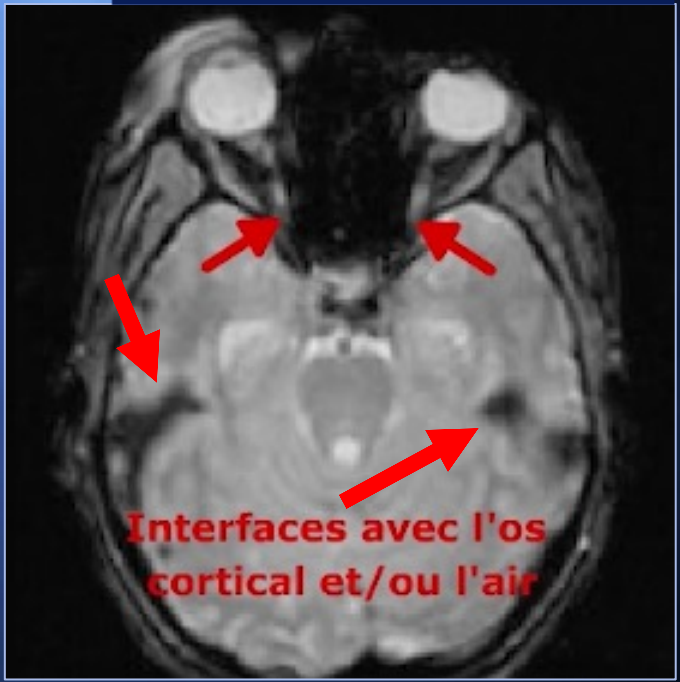


http://www.imaios.com/en/e-Courses/e-MRI/MRI-signal-contrast/90-RF-pulse

T_2* in MRI

- ✓ Loss of signal due to field inhomogeneities can be particularly marked close to boundaries between different tissues
  - soft tissue and bone, and close to air-filled sinuses
- ✓ resulting in significant image degradation and loss of diagnostic information



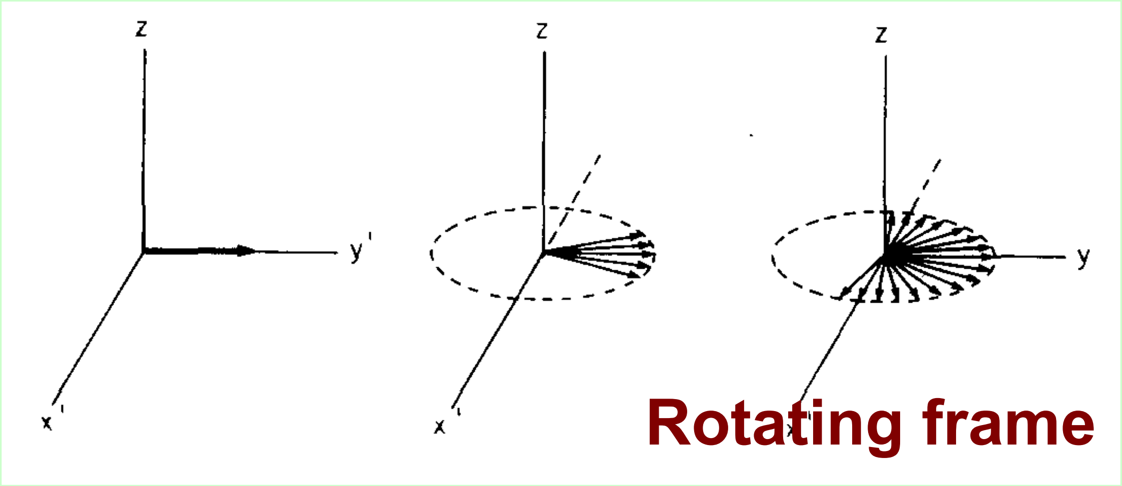


https://www.imaios.com/en/e-mri/image-quality-and-artifacts/magnetic-susceptibility

T_2* Relaxation

- ✓ *i* protons groups
  - isochromatis
- ✓ m_i magnetization of each group
- ✓ $M = \Sigma m_i$
- ✓ Field inhomogeneity $B_0 \pm \Delta B$

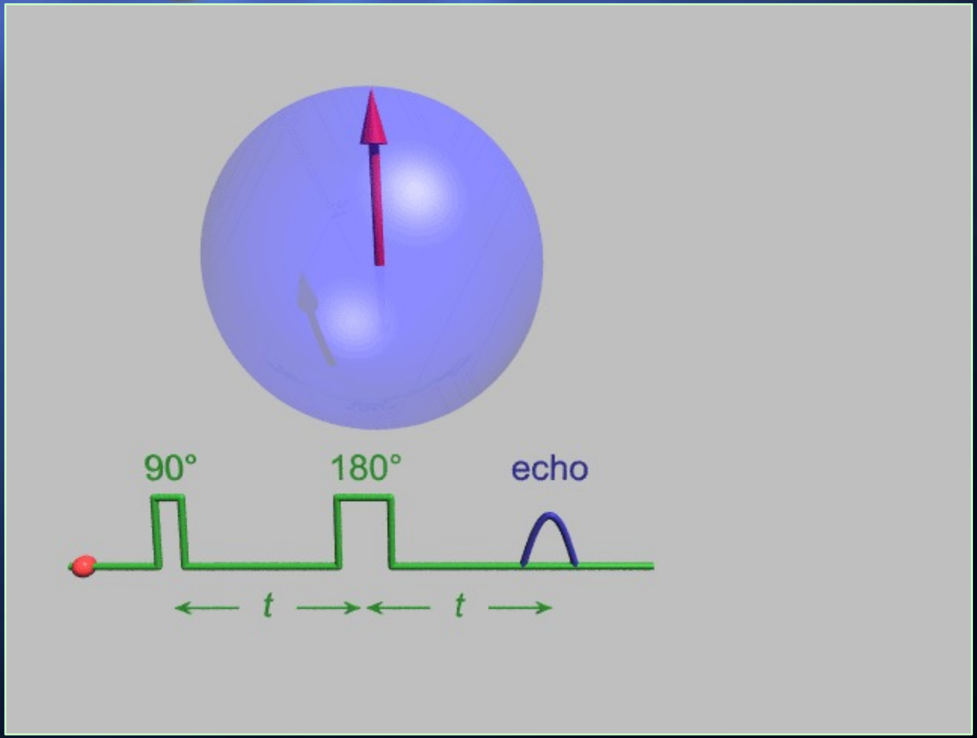
M_{xy} disappears at $t = \pi/(\gamma \Delta B)$



The spin-echo sequence

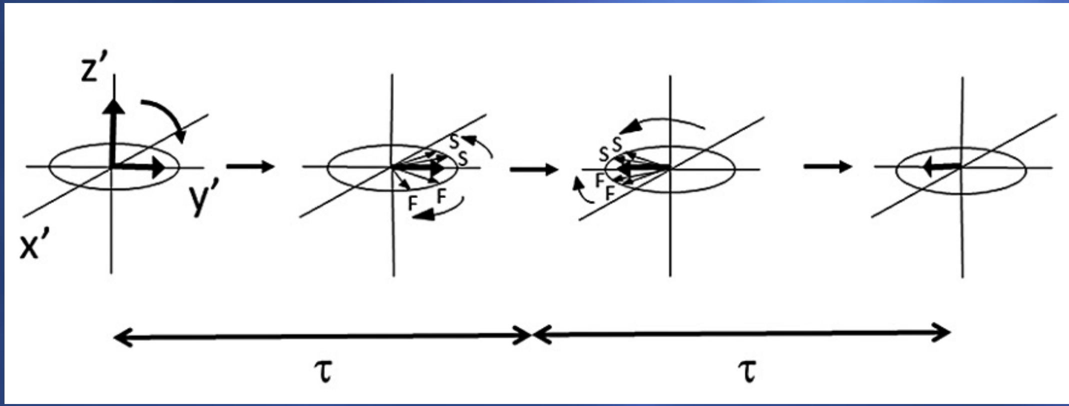
How measure T_2 in presence of ΔB ?

- ✓ The FID is dumped by T_2^*
- ✓ It is necessary to compensate the ΔB effect on spin dephasing
- ✓ 180° pulse along y' axis creates an echo signal
  - *Very approximated movie !!!*



T2* and spin echo

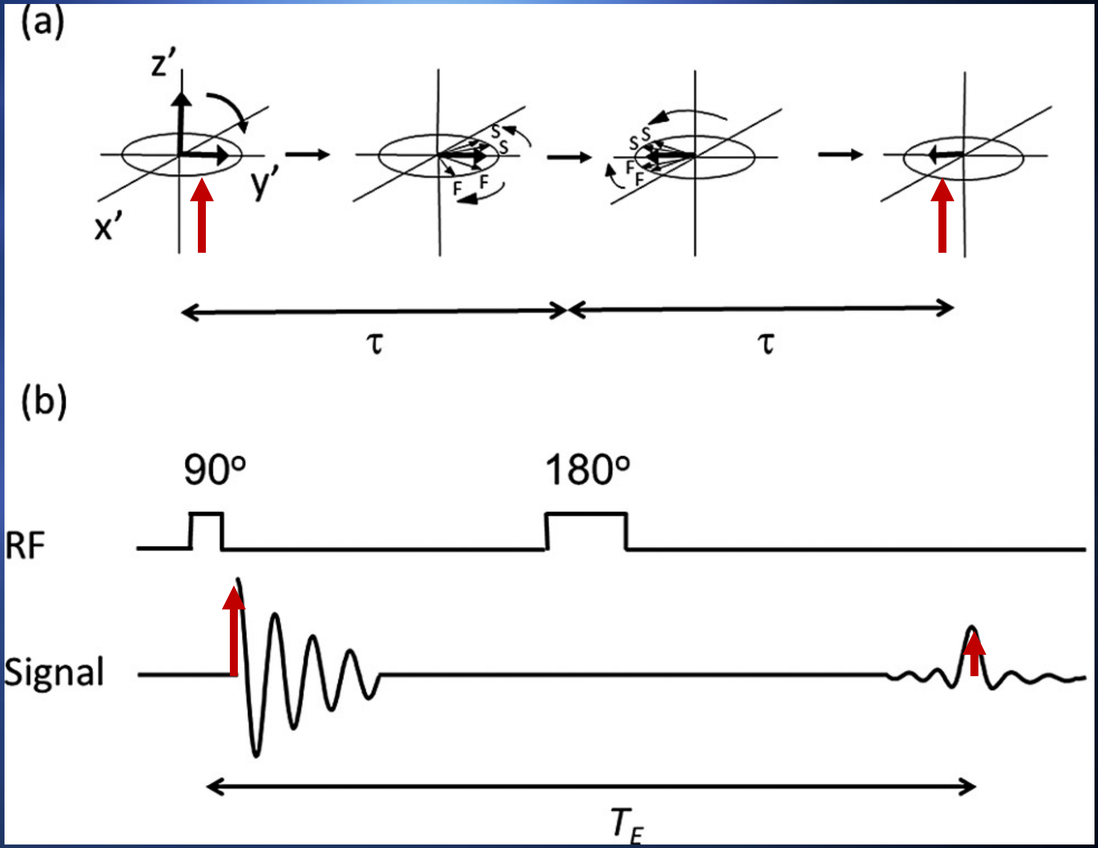
- ✓ At a time τ after the 90° pulse, another RF pulse is applied
  - nutating the magnetisation through 180° RF pulse



- ✓ The ‘fan’ of isochromats is ‘flipped’ to the other side of the transverse plane
  - now the ‘slow’ isochromats are in front of the net magnetisation vector and the ‘fast’ ones are behind
- ✓ After the 180° pulse the ‘fan’ begins to close, after another interval τ the M_{xy} is back in phase

T2* and spin echo

- ✓ the rephased M_{xy} is smaller than immediately after the 90º pulse
- ✓ the 180º pulse reverses dephasing, but not true T_2 decay during the 2τ time

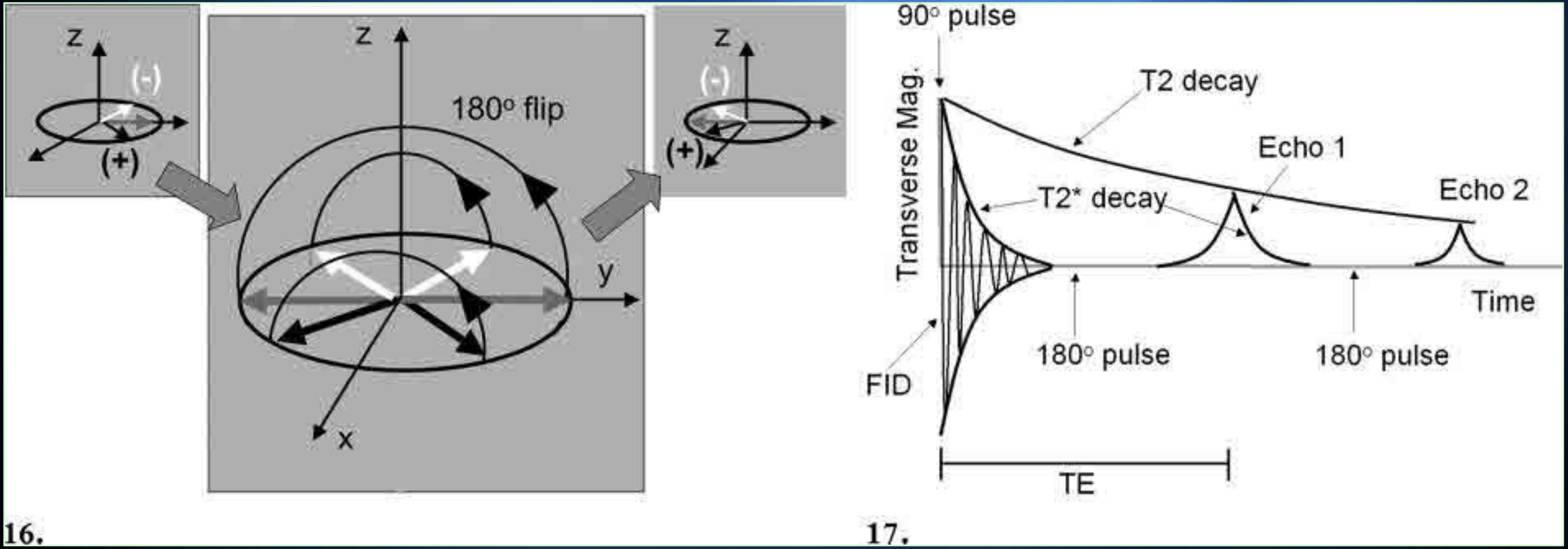


https://www.imaios.com/en/e-mri/nmr-signal-and-mri-contrast/180-rf-pulse

Spin echo signal

$$A(2\tau) = A_0 e^{-\frac{2\tau}{T_2}}$$

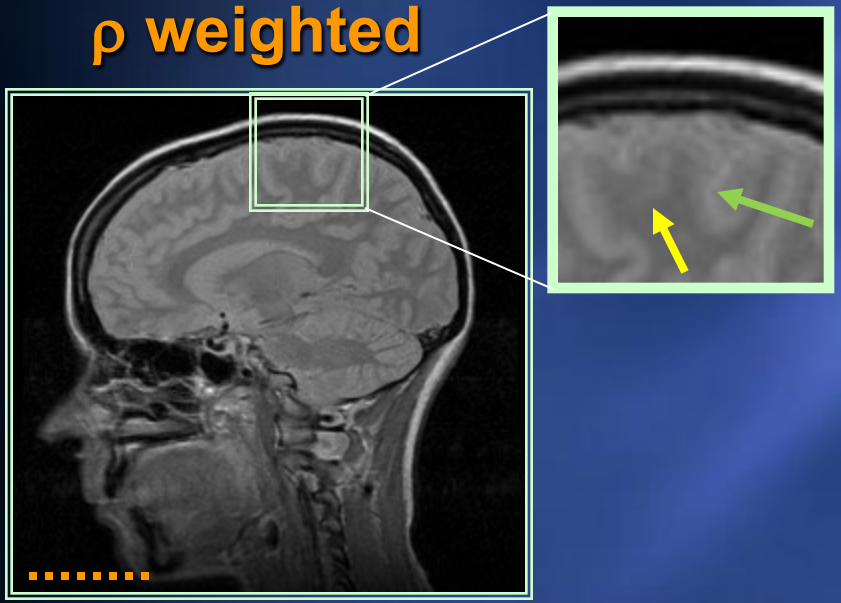
Echo time $T_E = 2\tau$



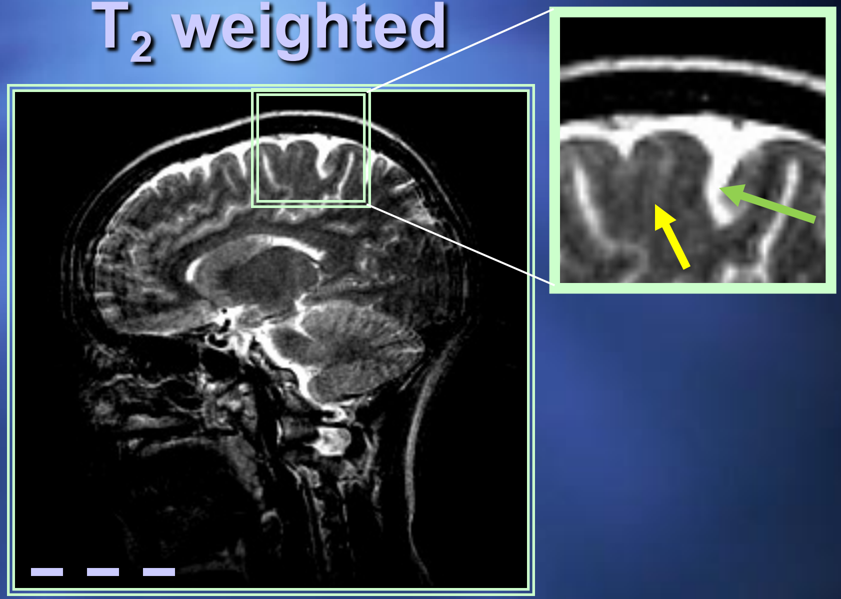
Pooley RadioGraphics 2005; 25:1087–1099

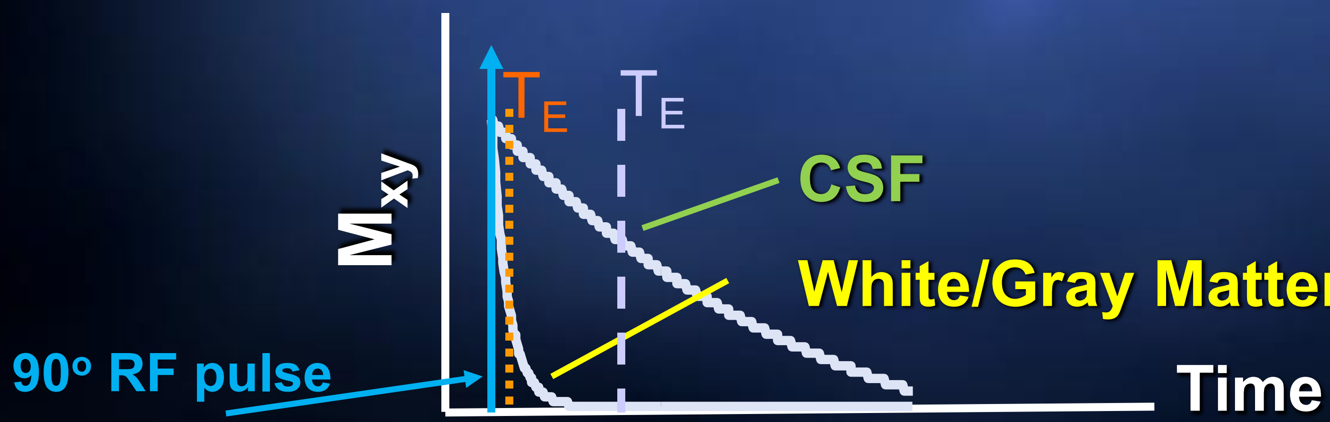
ρ and T_2 Contrast

Short Echo-Time
ρ weighted

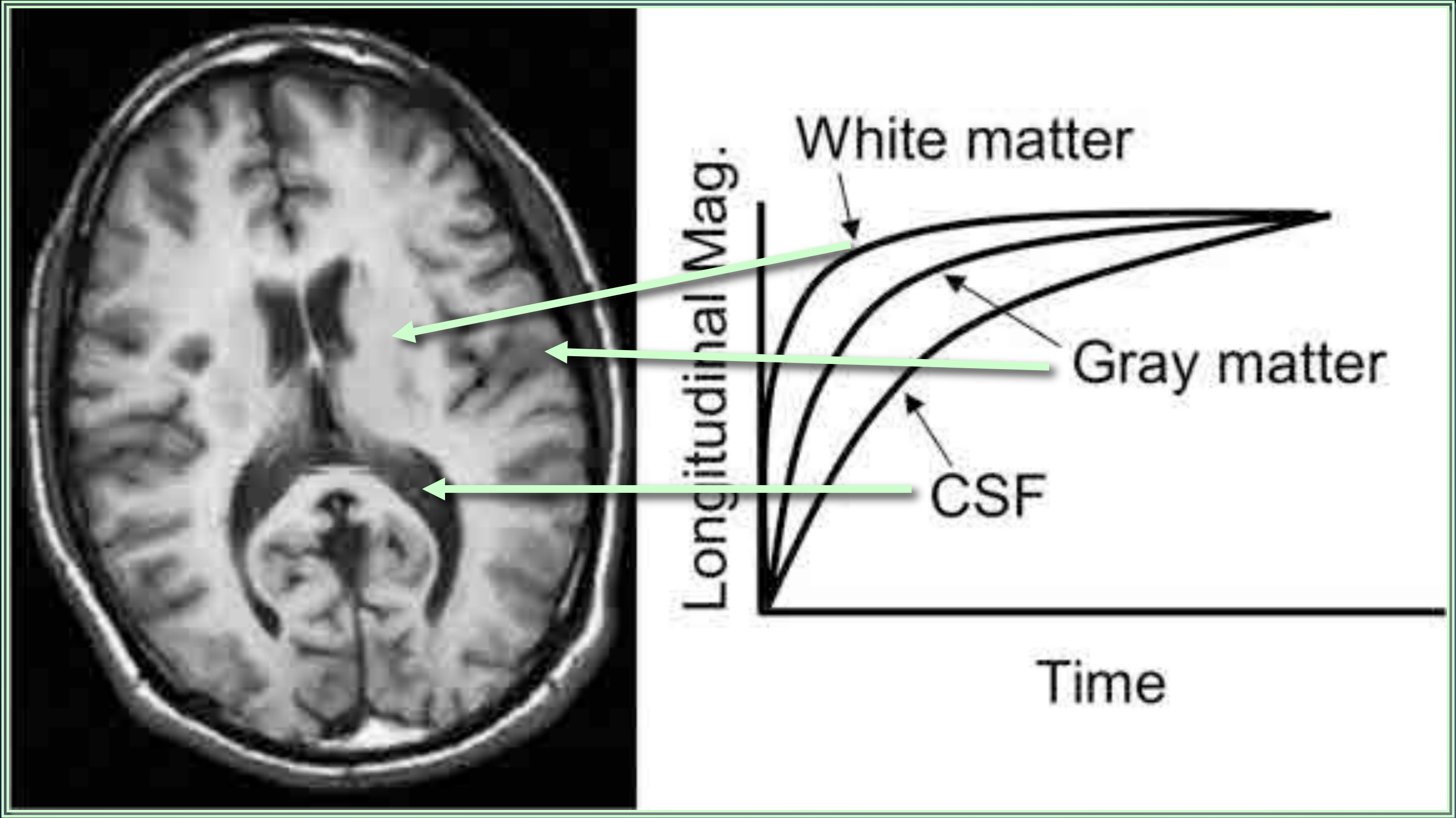


Long Echo-Time
T_2 weighted





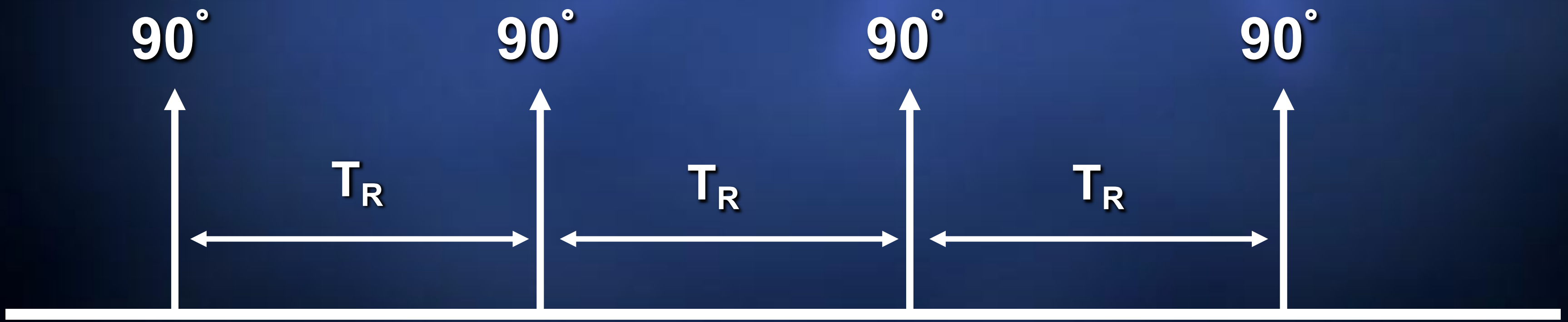
T1 weighted images



tissue	T_2	$T_1(H_o=0.5T)$	$T_1(H_o=1.5T)$
	(msec)	(msec)	(msec)
White matter	90	500	780
Grey matter	100	650	920
CSF	160	1800	2400

Repeated FID sequence

- ✓ Total saturation: when $M_z=0$
- ✓ Saturation Recovery sequence:
  the 90° pulse is repeated
- ✓ T_R: repetition time
  - T_R shorter than 3 T_1

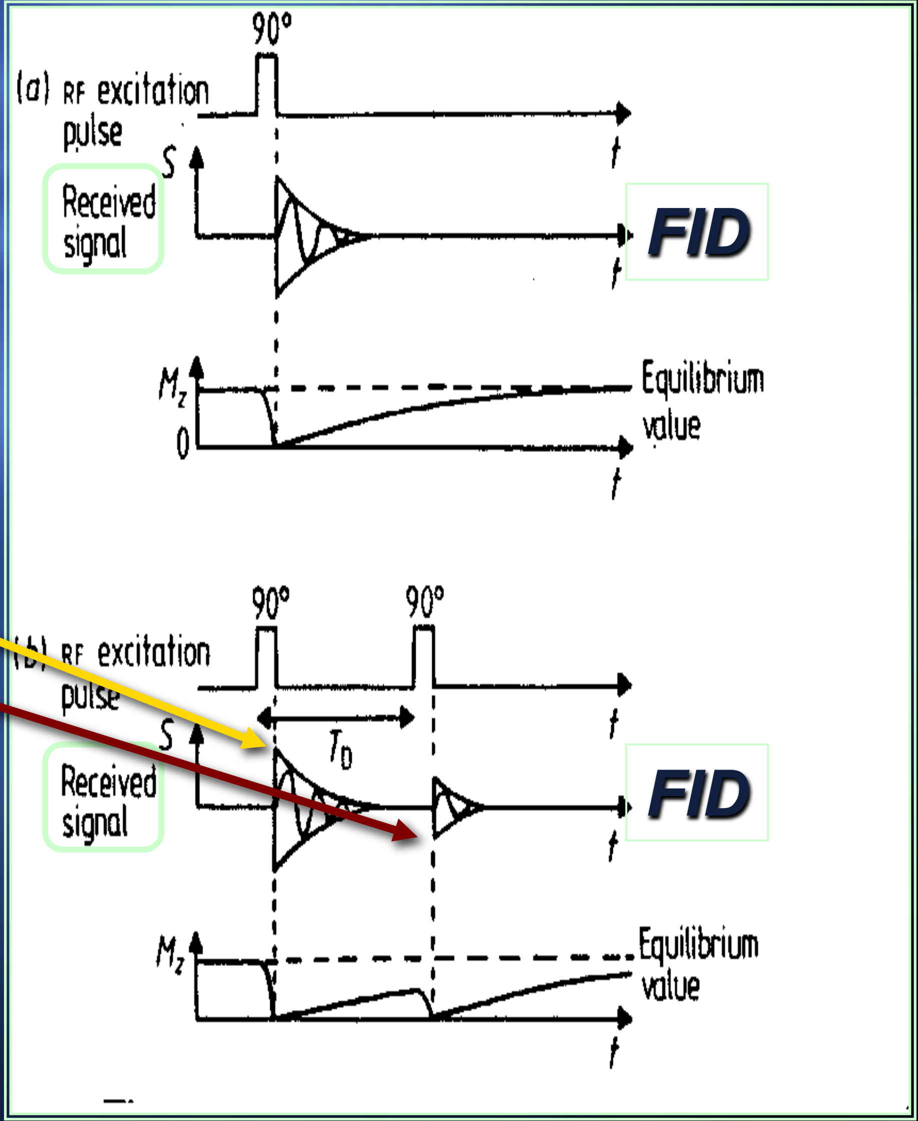


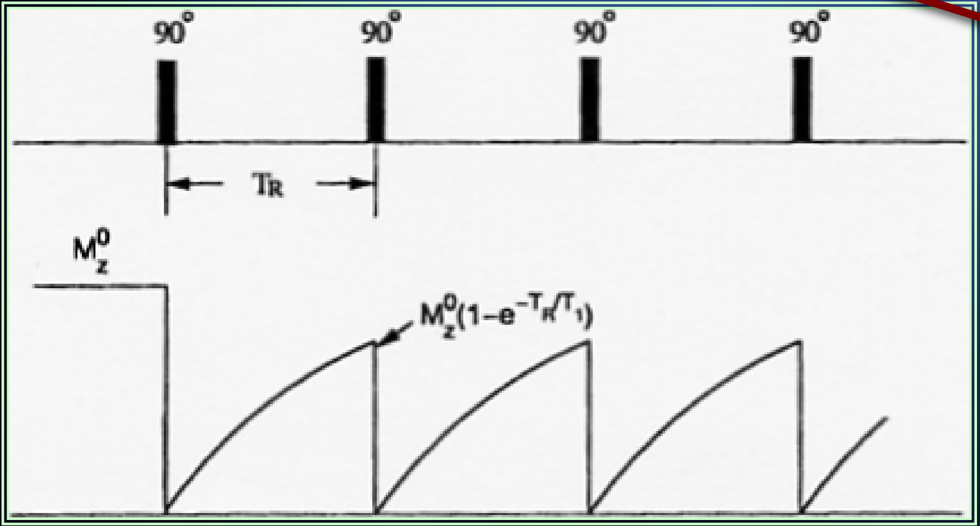
http://www.imaios.com/en/e-Courses/e-MRI/MRI-signal-contrast/TR-and-T1-weighting

SR signal intesity

$T_R < 3T_1$ partial saturation of the FID signal:

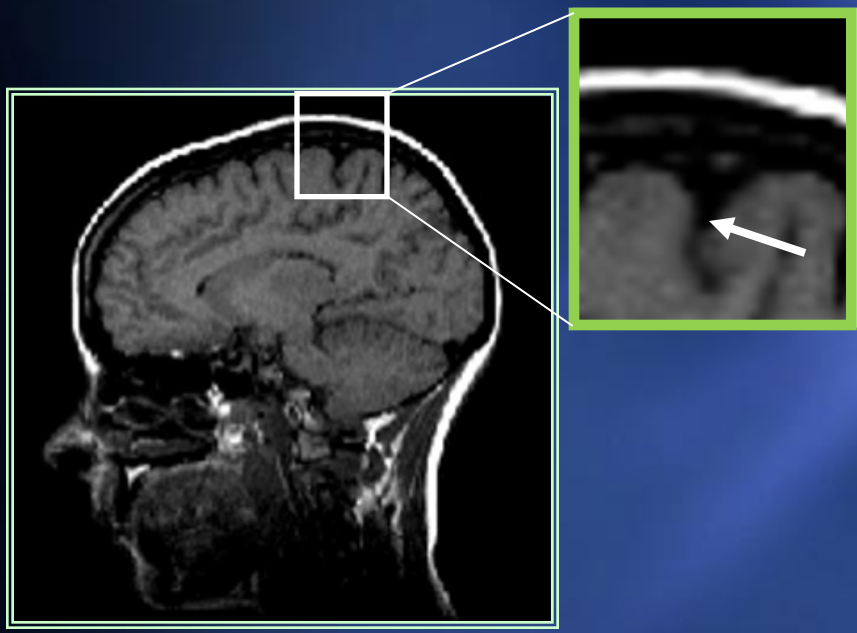
$$M_z^n(T_R) = M_z^0 \left[1 - e^{-TR/T_1}\right]$$

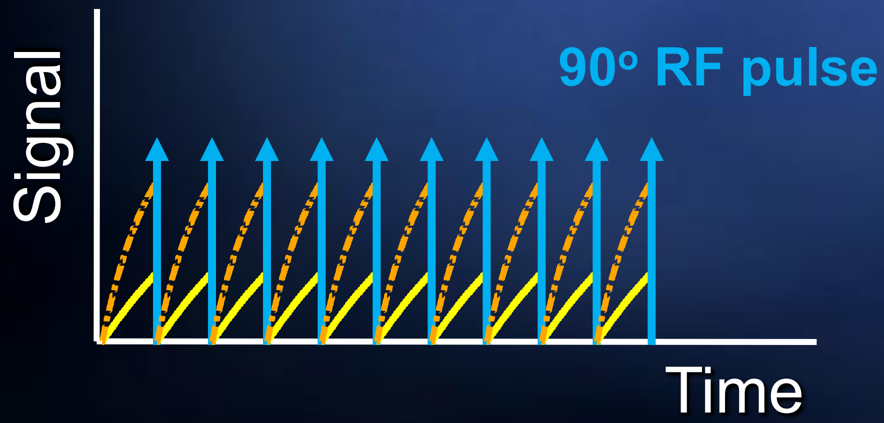




T_1 Contrast

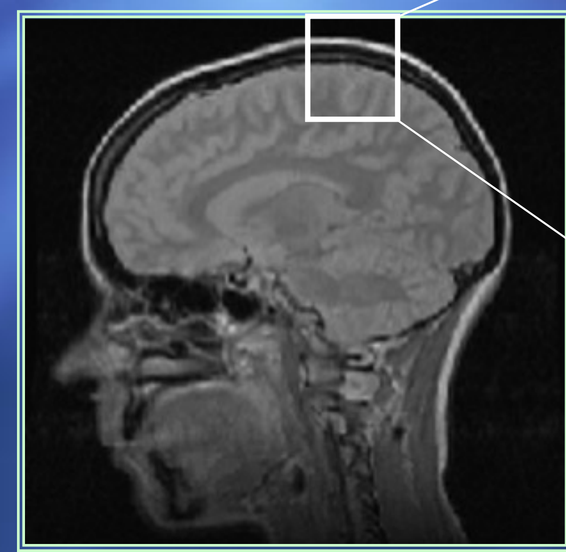
Short Repetition

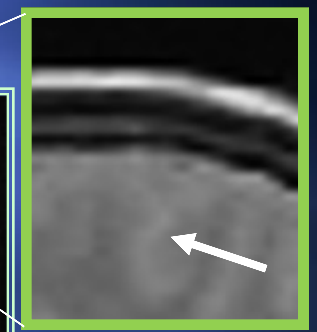


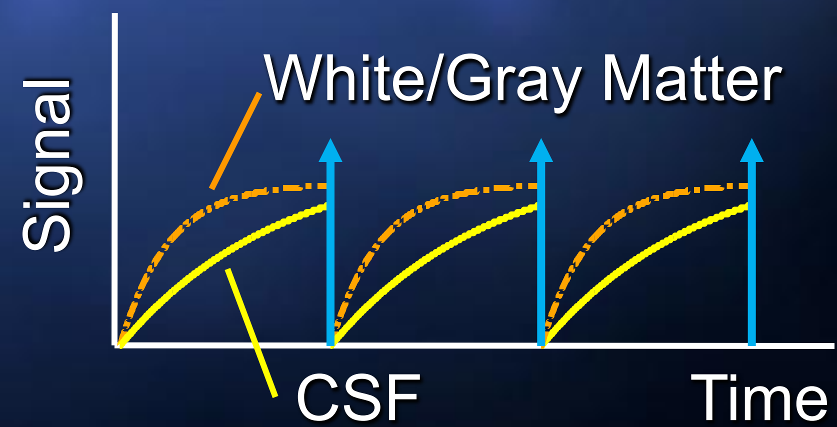


Long Repetition

No T_1 contrast







Pulse sequences

- ✓ The intensity of the NMR signals collected from different tissues at a given echo time depends on the T_1 and T_2 values of tissues
- ✓ The contrast in signal intensity between tissues will depend on T_E and T_R as well